Sediment dynamics and depositional environment on Panjang Island reef flat, Indonesia: insight from grain size parameters

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Abstract. Panjang Island Reef Flat is a remote area on Berau Continental Shelf with pristine ecological conditions. This site was selected to study the nature of sediment dynamics in tropical shallow waters. In addition, the sediment textural parameters provide good proxies for long term hydrodynamic process within the marine ecosystem. The aims of this study were to determine: (1) sediment textural parameters; (2) the transport mechanism of sediment particles; and (3) the depositional environment characteristics of the Panjang Island reef flat. The grain size parameters were further analysed to reveal the transport mechanism and energy regime. The results show the presence of coarse to fine sand sediments transported predominantly by rolling and suspension, with a sedimentary environment classified as Inner Shelf. These findings imply the incidence of gradual hydrodynamic energy attenuation at the shelf edge, characterized by breaking waves, followed by extensive seagrasses bed; these are collectively assumed to retard flow. This study suggests the subdivision of Panjang Island reef flat into two distinctive zones based on the ecological engineering capacity of seagrass, particularly regarding the influence on sediment particle distribution. The first comprises fine sand, and is associated with medium to large sized canopy seagrasses vegetation, while the second consists of medium to coarse sand, which is colonized by small to medium canopy sized seagrasses beds.

Key Words: sedimentary environment, Berau Continental Shelf, Derawan Archipelago, seagrasses.

Introduction. Sediments are unconsolidated material produced by the weathering process of rocks through mechanical or chemical processes. They are eroded, entrained, and transported to new locations which become a terminal or final deposition environment. The particle size and distribution are fundamental properties known to provide essential clues regarding the sample origin, susceptibility to entrainment, transportation, and depositional history (Folk & Ward 1957; Moiola & Weiser 1968; Folk 1974; McLaren & Bowles 1985; Blott & Pye 2001, 2012; McLaren 2014).

There have been several studies on sediments in aquatic environments in Indonesia, among others on sediments related to pollution, such as genotoxicity and volcanic mud (Risjani et al 2020a, b) and microplastic pollutants (Anggraini et al 2020). However, sediments on carbonate and reef systems in Indonesia are poorly studied (Solihuddin et al 2019). Therefore, it is important to investigate reef island sediment dynamics, including the variation in individual characteristics pertaining to ecological, geomorphological, oceanography and climate factors (Aldrian 2001; Aldrian et al 2007; Aldrian & Susanto 2003; Imran et al 2016; Solihuddin et al 2019).

The objective of this study was to determine the transport mechanisms and identify the depositional environment in a pristine reef system. This research was performed with samples collected at Panjang Island, in the Derawan Archipelago, northeast Kalimantan. Furthermore, investigations of this uninhabited island were carried out to determine the nature of sediment dynamics, based on the grain size parameter, in relation to the environmental conditions, including seagrasses assemblages.

Material and Method

Ocean geology and climate setting. Panjang Island is situated in the southern part of the Tarakan sub-basin (Wight et al 1993; Tossin & Kadir 1996; Suwarna & Hermanto 2007; Maryanto 2012). This location is also on the northern part of the Berau Continental Shelf in Northeast Kalimantan, about 15 km east of Tanjung Batu on the Kalimantan mainland, and about 110 km south of Tarakan Island. The 442 ha island is oriented from northwest to southeast and is bounded by a reef flat with a measured area of about 6000 ha, which forms a barrier reef system along the Panjang Island, also oriented NW-SE parallel to the shore. The Berau Continental Shelf is reported as having very flat reef characteristics, with a slope range from 0.05 to 0.8° (Christianen et al 2013). The intertidal and subtidal reef flats are naturally covered with seagrass vegetation and fringed by reefs on the outer edge (van Katwijk et al 2011).

The oceanographic conditions within the Derawan Archipelago are influenced by the Sulawesi Sea. According to Tarya et al (2010), hydrodynamic features on the Berau Continental Shelf are primarily driven by tides, wind and density differences. The tidal pattern is mixed and predominantly semidiurnal, with a range of about 1 m at neap tides and 2.5 m during spring tides. In addition, as a part of the Indonesian Maritime Continent, the Berau Continental Shelf is also influenced by the monsoon cycle. The Northwest and Southwest monsoons observed between December to February and July to September, respectively, are characterized by predominantly gentle (Beaufort Scale) and steady winds (Tarya et al 2015, 2018). Between these two monsoons, the annual monsoonal cycle comprises two transition periods, Transition I (March to June) and II (October to November), where wind strength is generally weak and wind direction tends to be more variable (Tarya et al 2015, 2018).

Sampling and data analysis. Samples weighing around 0.5 to 1.0 kg (wet weight) of surface sediment deposited within the subtidal area of Panjang Island were collected from 15 locations (Figure 1). These samples were then stored in sealed ziploc-bags, and subsequently evaluated for grain size at the Laboratory of Water and Environmental Quality, University of Borneo, Tarakan, Indonesia. Prior to analysis, the samples were dried for 24 h in a hot air oven at 40°C to eliminate moisture, then approximately 200 g of each sample was measured and subjected to sieve analysis using the American Society for Testing and Material (ASTM) sieving protocols. The sifted material was collected in fractions, weighed, and the individual values recorded were tabulated for textural analysis. Seagrass density, cover and species composition were recorded *in situ* using 0.25 m^2 quadrat transects, based on standard protocols (Duarte & Kirkman 2001; McKenzie & Campbell 2002; Rahmawati et al 2014).

The sediment texture and grain size statistics (mean, standard deviation/sorting, and skewness and kurtosis) were generated using Gradistat v.8.0 software (Blott & Pye 2001). Grain size classification and types were defined based on Blott & Pye (2012), while sediment transport mechanisms were evaluated using a CM bivariate plot (Passega 1964; Passega & Byramjee 1969). This assessment originally relates the transport conditions of the marine sediment prior deposition to grain-size parameters (C99 vs. median grain size). Specifically, C represents the one percentile while M is the median of sediment grain size distribution parameters, and both statistics are obtained from the Gradistat output in microns or ϕ units. According to Passega (1964), the "C" value is the first coarsest percentile (D99), but this study used the D90 present in the plot, as suggested by Nugroho & Putra (2019). A somewhat higher percentile was selected to avoid the statistical effect of abnormally coarse grains present within the specific size distribution (El Talibi et al 2016).

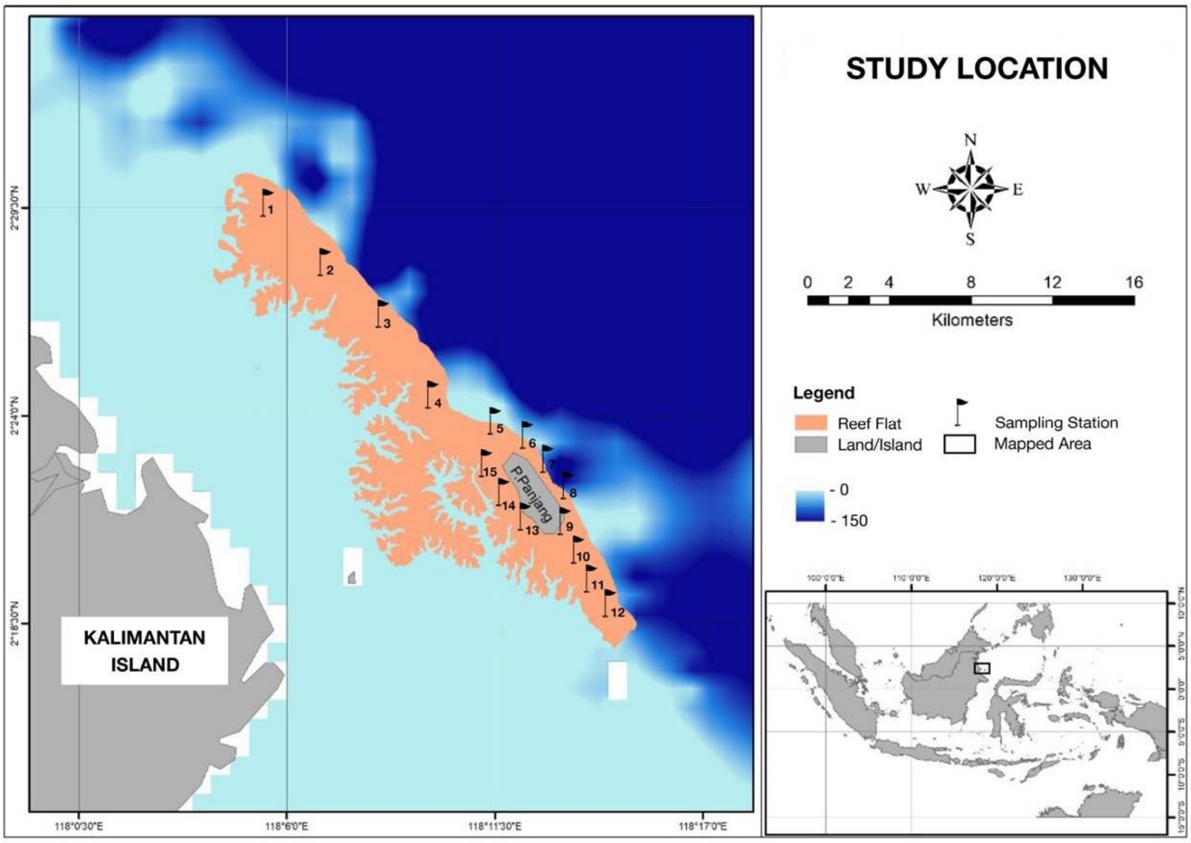

Figure 1. Map of Panjang Island, East Kalimantan, Indonesia, showing the study area and the surface sediment sampling locations on the reef flat.

The energy processes within the environment where the sediments are deposited was assessed using a bivariate plot between median vs sorting in ϕ scale, also known as a Stewart Diagram (Stewart 1958). This approach was used to further interpret the hydrodynamic conditions (Kanhaiya et al 2017). Subsequently, the CM and Stewart Bivariate Plots were generated with PAST: Paleontological Statistics version 3.22 (Hammer et al 2001). The predominant hydrodynamic energy was identified by overlaying the sediment textural triangle on the textural characteristics and associated environment, as reported in Mathews et al (2007). This ternary diagram was introduced based on a similar study on texture distribution at the Great Barrier Reef, Australia.

Results and Discussion

Sediment grain size and seagrass meadow characteristics. Table 1 shows the textural parameters of surface sediments and general morphometric and species composition characteristics of the seagrass meadows. The results showed the presence of seagrass meadows characterized by multi-species composition; one of three species (*Halophila ovalis*, *Halodule uninervis*, and *Thalassia hemprichii*) dominated the seagrass community in all stations. There was a marked shift in species composition from the northern reef flat, dominated by *T. hemprichii*, to *H. uninervis* which was mostly observed in the south, while *Enhalus acoroides* was specifically limited to the west side of Panjang Island.

Table 1

Grain-size parameters of the samples analysed and characteristics of the seagrass meadows in the sampled area

St	*Sediment textural properties*									*Seagrass meadow properties*		
	Gravel (%)	*Sand (%)*	*Mud (%)*	*Mean (ϕ)*	*Sorting (ϕ)*	*Skewness (ϕ)*	*Kurtosis (ϕ)*	D_{50} (μm)	D_{90} (μm)	*Density (shoot m⁻²)*	*Cover (%)*	*Species*[a]
1	17.4	82.5	0.1	0.972	1.751	0.115	0.670	548.5	2146.2	436	42.5	Ho, Cr, Si, Th*
2	14.4	85.5	0.1	1.298	1.590	0.247	0.657	535.5	2103.0	216	36.25	Ho, Si, Th*
3	16.6	83.4	0.0	0.965	1.742	0.122	0.678	554.4	2135.8	248	37.5	Ho, Si, Th*
4	17.2	82.7	0.2	0.978	1.754	0.117	0.671	547.8	2143.0	657	43.75	Ho, Cr, Si, Hu, Th*
5	15.1	84.8	0.0	1.177	1.508	0.245	0.925	563.1	2115.3	1515	53.75	Ho, Cr, Si, Hu, Th*
6	21.2	78.7	0.1	0.906	1.735	0.124	0.911	572.8	2182.9	1279	57.5	Ho, Cr, Si, Hu, Th*
7	16.0	83.9	0.1	0.958	1.733	0.123	0.916	557.0	2128.1	2129	68.75	Ho, Cr, Si, Hu*
8	20.4	79.6	0.0	0.906	1.726	0.117	0.912	568.1	2175.7	2096	67.5	Ho, Cr, Si, Hu*
9	13.8	86.2	0.1	1.195	1.511	0.237	0.933	552.1	2092.8	1288	66.25	Cr, Si, Hu*
10	12.4	87.6	0.1	1.192	1.499	0.240	0.931	553.9	2064.1	2000	68.75	Ho, Si, Hu*
11	16.4	83.5	0.1	0.955	1.730	0.111	0.675	549.5	2133.6	2221	71.25	Ho, Si, Hu*
12	12.6	87.4	0.1	1.242	1.541	0.247	0.686	544.6	2068.9	2235	76.25	Ho, Cr, Si, Hu*
13	5.4	94.5	0.1	2.438	1.358	-0.553	1.472	138.9	1053.2	237	63.75	Ea, Cr, Ho, Si, Th*
14	4.8	95.1	0.1	2.455	1.244	-0.508	1.236	137.9	1028.7	413	67.5	Ea, Cr, Ho, Si, Th*
15	2.6	97.2	0.2	2.724	1.049	-0.387	1.213	136.6	574.2	223	71.25	Ea, Cr, Ho, Si, Th*

[a] Ho: *Halophila ovalis*; Cr: *Cymodocea rotundata*; Si: *Syringodium isoetifolium*; Th: *Thalassia hemprichii*; Hu: *Halodule uninervis*; Ea: *Enhalus acoroides*; * indicates the dominant species.

The sediment collected from the studied area ranged from fine to gravelly sand. These materials were categorized as biogenic due to their composition comprised of shells and carbonate skeletons produced by living organisms, mostly material produced from the weathering of coral reefs with size reduced by hydrodynamic processes. This composition indicates nearshore zones and adjacent shoal areas as the main sources of sediment materials. This finding was congruent with a report by Solihuddin et al (2019) from Karimunjawa, where the corals and other shell-forming organism were recognized as the major contributors to carbonate sand and gravel deposits in the reefs sediment.

Table 1 and Figure 2a show the average mean size of the Panjang Islands Reef Flats surface sediments at 1.36 ϕ, which varies from a maximum of 0.91 ϕ to a minimum of 2.73 ϕ. Furthermore, the predominant samples exhibit coarse and medium sand (station 1-12), while the remainder (station 13-15) are in the fine sand category. Table 1 and Figure 2b show a skewness range of -0.39 φ to 0.25 φ, where Station 1-12 are fine skewed or positive skewness, as indicated by excess fines (Blott & Pye 2001; Folk & Ward 1957). Conversely, stations 13-15 were very coarse, with negative skewness. All evaluated samples were poorly sorted, and ranged from 1.05 to 1.76 φ, with variations in kurtosis value from very platykurtic to leptokurtic (Table 1; Figure 2c and 2d).

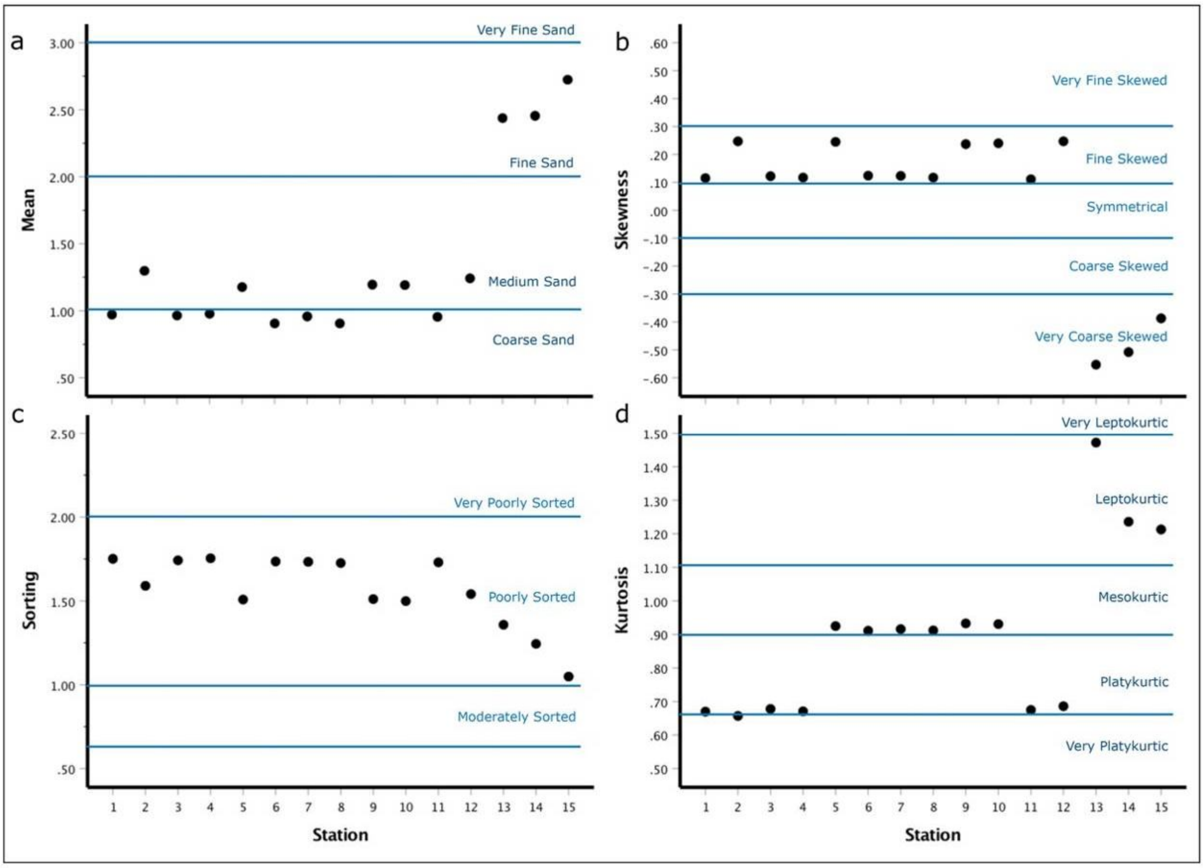

Figure 2. Textural parameters of Panjang Island reef flat surface sediment (a) mean, (b) skewness, (c) sorting and (d) kurtosis, all in ϕ unit.

The mean size is a function of the size range of available sediment material dimension and the amount of energy imparted. This is dependent on the current velocity or turbulence of the transporting medium (Folk 1974). Furthermore, the mean size is influenced by the supply source, transporting medium, and the energy level of the depositing environment (Folk & Ward 1957; Sahu 1964). Moreover, discrepancies in mean size indicate variation in the energetic condition of oceanographic regime over the Panjang Island reef flat. The fine grained sediment characteristics observed at stations 13-15 implies a possible deposition by weak current and wave conditions, due to the moderate shelter provided against the open ocean by the landmass of the island. These findings conform to the postulate of Folk (1974), which indicated the tendency to obtain finer materials with lower transport medium energy, while the mean size is directly correlated with shear velocity. Flemming (2000) identified a relationship between the particular grain size and critical shear velocity. This phenomenon was principally based on incipient motion, through the transition from a stationary to an initial (incipient) motion state as a response to increased hydrodynamic forces acting on a bed of unconsolidated deposits (Simões 2014).

Folk (1974) suggested the concept of sediment textural maturity, based on the effect of coastal hydrodynamic processes on texture distribution. This indicates an increase in value as sediments suffer greater mechanical impact through the abrasive and sorting action of waves or currents. Furthermore, the materials pass sequentially through the following four stages: immature, submature, mature and supermature (Folk 1974). Folk (1974) provided a descriptive scale of textural maturity based on sorting values, which is known to indicate the environmental effectiveness in winnowing, sorting, and abrading of furnished sediments (Figure 3). The samples obtained show poor sorting, and are thus classified in the submature category.

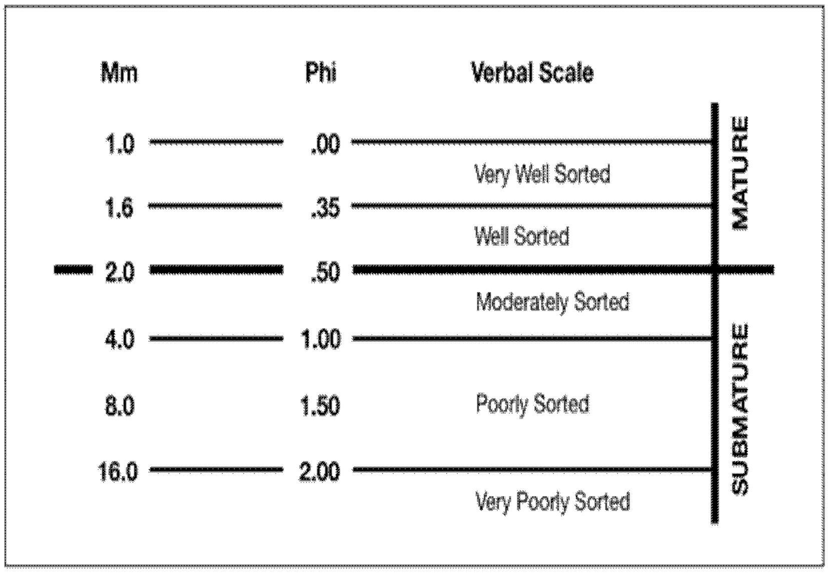

Figure 3. Relation between textural maturity and sorting, more detailed information on the description and integration properties can be found in Folk (1974).

Garzanti (2017) disagreed with the concept of sediment textural maturity, and states that poorly and well sorted sediments are deposited immediately, under the dominant action of gravity and traction currents, respectively. Thus, the sediment sorting value would not have a significant relation with the progressive accumulation of “modifying energy” through time, and considered that there was no such thing as a constant sequential order of sediment textures (Garzanti 2017). Nevertheless, in this case, both seem to agree that waves, currents, and gravitational forces sort and rework the surface sediment on the reef flat as the tides continuously rise and fall. Thus, the sample sorting value is considered to directly reflect the net fluctuation of hydrodynamic energy exerted across the Panjang Island Reef Flat.

In terms of particle shapes, the poorly sorted sediment implies that most of sediment particles have an irregular shape. The sediment samples studied were irregular in shape because they originated from coral rubble and the shells of calcareous organisms that had been weathered. These findings are congruent with the report by Flemming (2016), where the well-rounded grains tend to achieve a higher sorting value than irregular ones under similar hydrodynamic conditions.

Sediment transport mechanism. Figure 4 shows the bivariate plots representing a complete tractive current model. According to Passega (1957, 1964) and Passega & Byramjee (1969) the C-M diagram is formed by sample points of a deposit defined by C, the one-percentile, and M, the median of the grain-size distribution, where the data are plotted at logarithmic scales. Passega & Byramjee (1969) distinguished three basic limits, including Cr (C – rolling), Cu (C – uniform suspension) and Cs (C – graded suspension). In particular, the Cr line was the lower diameter limit/boundary of the particles transported through rolling mechanisms on the seabed. The Cs line was determined as the maximum threshold of samples conveyed in the stratified suspension form, while Cu denotes the maximum limit of homogeneously suspended particles (Mycielska-DowgiaŁŁo & Ludwikowska-Kedzia 2011; Passega & Byramjee 1969). Passega & Byramjee (1969) subdivided certain areas of the plot (Figure 4) marked by the points N, O, P, Q, R, S, T. This conforms to a particular sedimentation mechanism, where N represent samples transported exclusively through rolling, while OP transport through rolling with a contribution of suspension. In addition, PQ involves suspension with a level of rolling, QR transport in graded suspensions (mainly through saltation), RS transport in a homogeneous suspension, and T features settling from suspension in quiet water (Mycielska-DowgiaŁŁo & Ludwikowska-Kedzia 2011; Passega & Byramjee 1969).

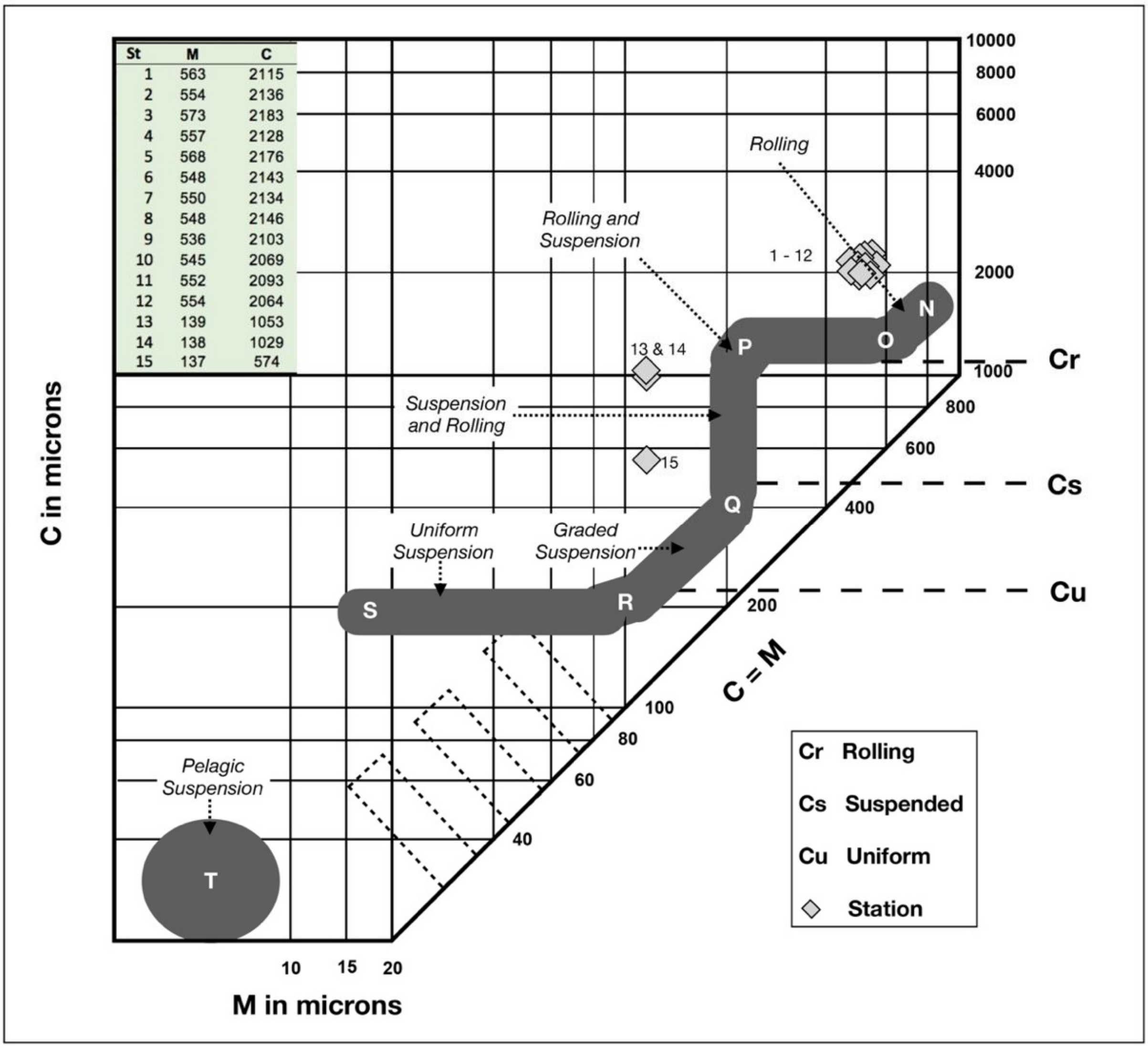

Figure 4. CM diagram of Panjang Island reef flat surface sediment (modified from Passega & Byramjee (1969)).

The diagram in Figure 4 shows rolling and bottom suspension as the most prominent transport mechanisms. In addition, stations 1-12 lie around the NOP segment, indicating rolling as the dominant transport mode, with few contributions from suspension. This can be explained by the fact that there were few sediments intermediate in size between those transported through rolling and those easily resuspended. The transport mechanism for stations 13-15 (PQ) was mainly by suspension with minor input from rolling particles. Passega & Byramjee (1969) noted that this segment comprises sediments that formed by suspension (represented by point Q), while the rolled grains constitute a small proportion, estimated to have little or no effect on the median value.

Based on the classification of the hydraulic sedimentation modes in Figure 4, we can trace the history of the transport and deposition processes. These findings imply the complexities in the hydrodynamic processes that operate in these reef flat systems. Stations 1-12 exhibit characteristics typical of sediment that has distributed by relatively strong hydrodynamics induced by waves and currents capable of triggering bottom turbulence. This phenomenon consequently facilitates particle movement. However, the water hydrodynamics at stations 13-15 are not strong enough to trigger sufficient turbulence for particle transportation through a rolling mechanism. Hence, only materials with smaller particle size were entrained and transported.

Depositional environment. Stewart (1958) originally proposed the relationship between sediments and depositional environment through a graphical representation known as the “Stewart Diagram,” such as that shown for Panjang Island in Figure 5. Using the bivariate plots of median and sorting, three environmental groups of sedimentary processes were established, including (1) wave action, consisting of normal oceanic processes shoreward of the surf zone; (2) river processes, primarily floods; and (3) slow deposition from quiet waters (Stewart 1958). The undefined segment of the plot was then grouped as inner shelf processes (Jagodziński et al 2012; Parthasarathy et al 2016; Kanhaiya et al 2017; Lukman et al 2018). The bivariate plots of median and sorting of Panjang Island, Reef Flat, show the samples were deposited through inner shelf processes (Figure 5).

Flemming (1982, 2011) and Flemming & Fricke (1983) described the inter-relationship between beach morphodynamics, wave climate and grain size (Figure 6). Beach morphodynamics are essentially the result of interaction between waves and marine sediments. Based on the mean size and beach slope, the Panjang Island reef flat presents two distinct characteristics, including a dissipative state (stations 1-12), and a transition from the dissipative to intermediate domain (stations 13-15). Under these conditions, stations 13, 14, and 15 positioned at the west side of Panjang Island, are expected to vary somewhat in oceanographic or hydrodynamic conditions compared to the other stations.

Mathews et al (2007) classified the predominant character of each depositional environment based on sediment texture and sample location. Figure 7 exhibits the sediment of Panjang Island Reef Flat with associated predominant hydrodynamic process. These findings confirm the separation of Panjang Island reef flat morphodynamics based on the Fleming Diagram (Figure 6). Moreover, as explained by Tarya et al (2010), the tidal propagation over the Berau Continental Shelf has a cross-sectional pattern over the reef flats where the tidal amplitude increases due to the shoaling effect, which is then immediately followed by a decrease due to sea bed friction. The presence of Panjang Island has influenced the patterns of the tidal currents and waves around it.

In line with the Flemming Diagram illustrated in Figure 6, the mean size distribution (Figure 8) highlights the influence of the waves on sediment dynamics in relation to the Monsoon Cycle. During the Southwest Monsoon (June-September), the hydrodynamic strength at stations 13, 14 and 15 tends to increase due to exposure to incoming waves. The other stations were spread out and relatively exposed to open ocean (Sulawesi Sea). Hence, in both the monsoon and the transition periods, hydrodynamic effects tend to not vary significantly in the more exposed areas.

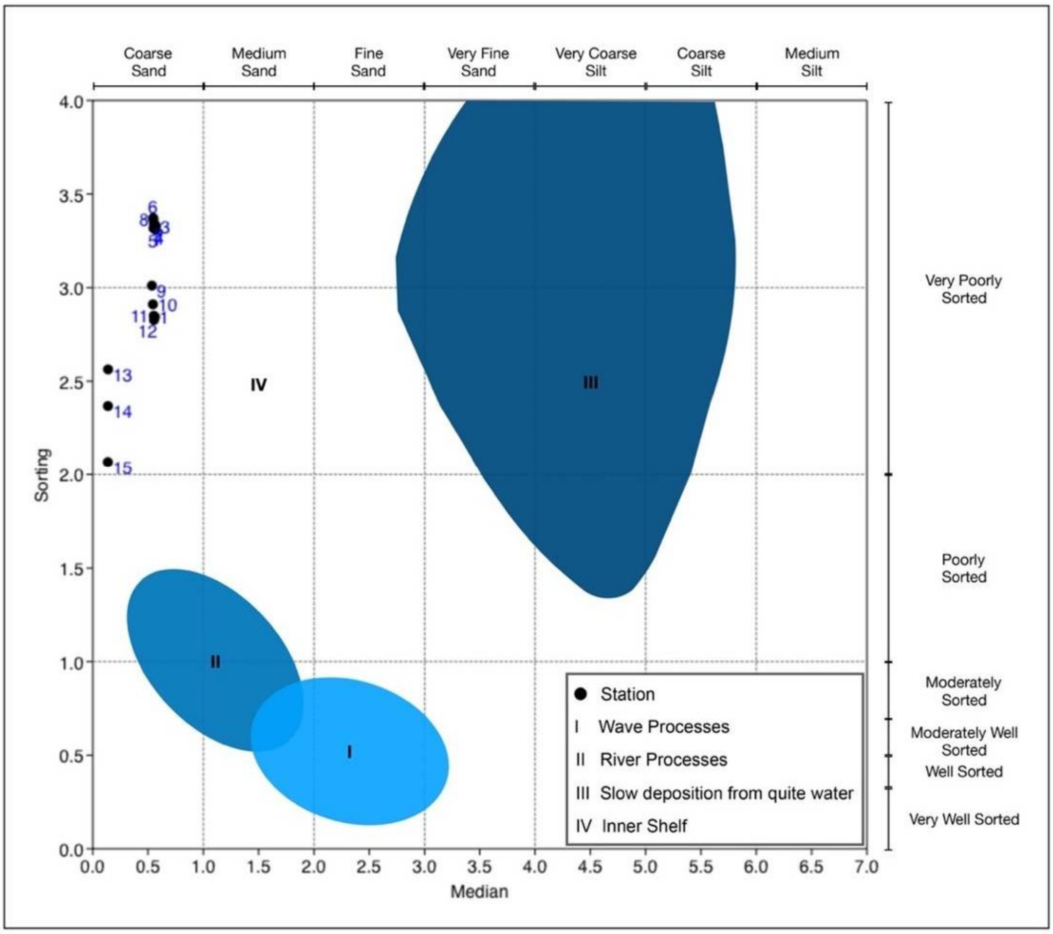

Figure 5. Position of all analysed sediment samples from the Panjang Island reef flat surface on the Stewart bivariate plot diagram with sorting values plotted against the median in ϕ scale.

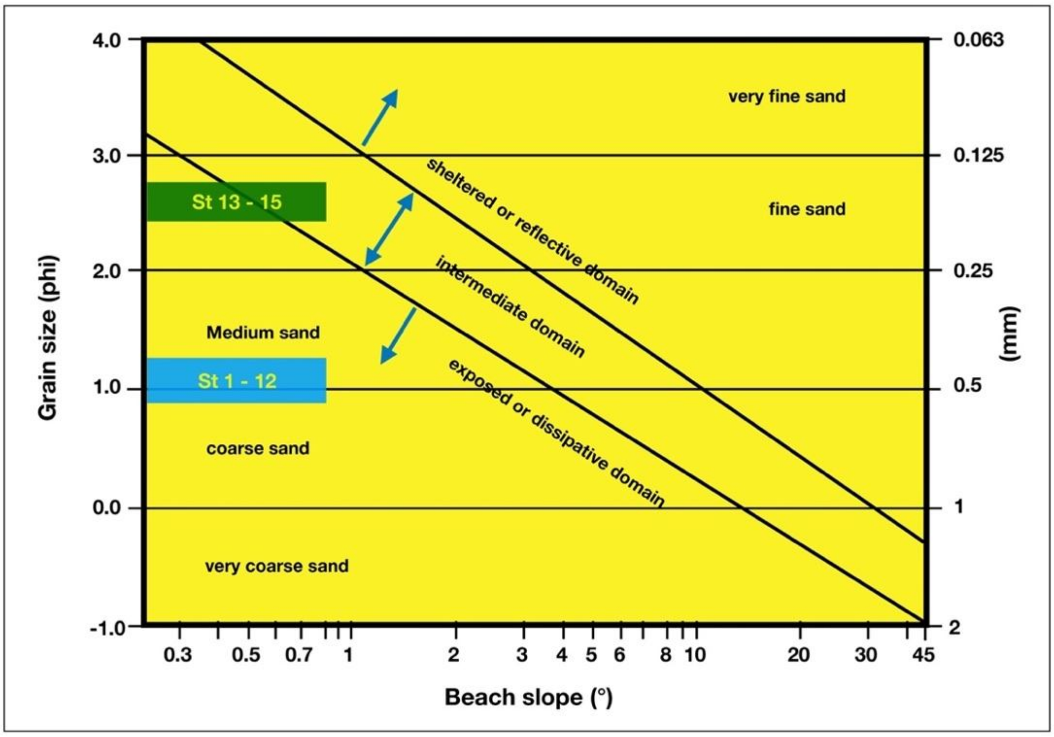

Figure 6. Plot of sediment grain size against the beach slope profiles revealing the morphodynamic character of the Panjang Island reef flat.

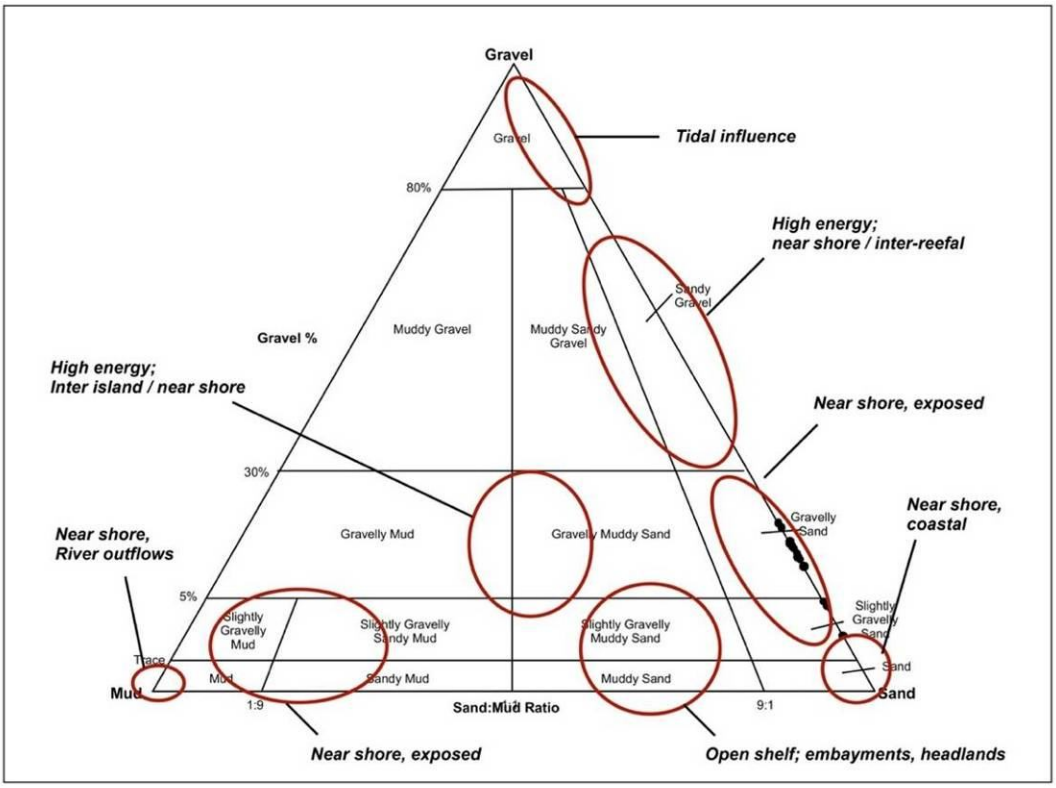

Figure 7. Ternary diagram showing the textural characteristics of Panjang Island reef flat surface sediment and associated inner shelf sediment environments.

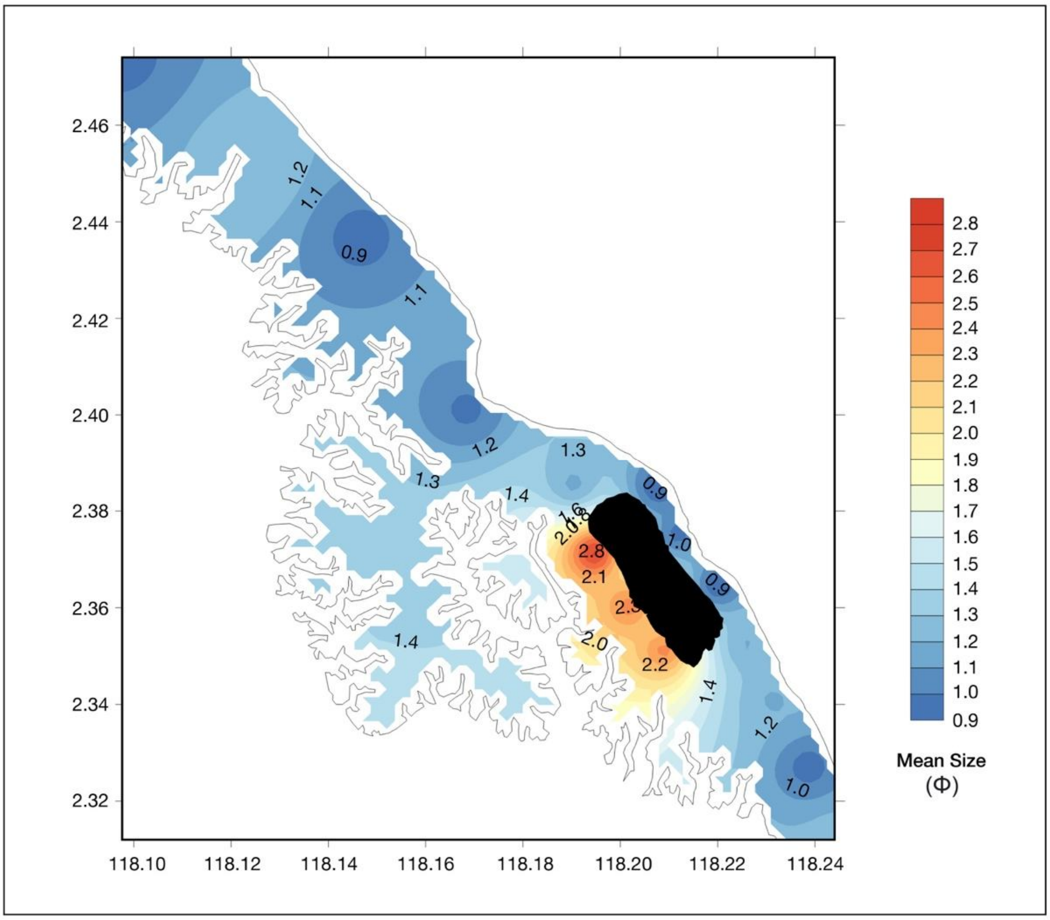

Figure 8. Mean size (ϕ) of surface sediments on the Panjang Island reef flats.

Influence of seagrass beds on sediment dynamics. The presence of seagrass beds influences the ability of waves and currents to transport sediment particles. These beds modify the hydrodynamic environment by: (1) attenuating current and wave energy loss, (2) changing the velocity profile close to the bottom to avoid affecting the thicker boundary layer, (3) increasing or decreasing turbulence and advancing material transport (4) monamist propagation, or leaf waving to increase advection (Madsen et al 2001; Koch et al 2006; Potouroglou et al 2017; Lanuru et al 2018). The ability of seagrass to inhibit sediment movement has been reported, including for small seagrass species Christianen et al (2013) and Paul (2018). Lanuru et al (2018) have shown that seagrass species present in the Spermonde Islands, Indonesia (an archipelago somewhat similar to our study area) reduced turbulence, intensity, and shear velocity by proportionately varying amounts based on canopy height, leaf blade density and morphometry.

Conclusions. This study evaluated the dynamics of Panjang Island reef flat surface sediments in East Kalimantan, Indonesia, based on the grain size or textural sediment parameters to assess the sedimentary environment. Sediment dynamics were affected by several factors that influence particles and these factors simultaneously interact with each other. Moreover, wave energy and the tides are known to trigger sediment particle movements, while in contrast the existing seagrass beds are responsible for holding some sediments in place. Spatially, the Reef flats of Panjang Island were categorised into two zones with distinct sedimentary and environmental characteristics, where the first occurs along the west side of Panjang Island, and is characterized by a relatively calm environment. This zone also features larger seagrass species forming a medium to high canopy, and promotes the deposition of finer sand particles. Meanwhile, the second zone extends to the remaining area from the northwest tip along the east side of Panjang Island to the southeast end of the Reef. This region was more exposed to wave, current as well as tidal forces, and the properties included moderate to coarse sand sediments colonized by seagrass beds categorised by smaller species with a lower canopy height.

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